GPS Measurements, Fault Stress Modeling and Integrated Earthquake Hazard Assessment of the Wasatch Front, Utah

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Investigations Undertaken (October 1, 1999 to September 30, 2000):

The above research project focused on investigations of the Wasatch fault, Utah, using continuous and campaign GPS measurements to assess the contemporary state of strain, the physics of normal faulting earthquakes and the contemporary deformation contribution to earthquake hazard. Elastic fault stress modeling incorporated a new inverse fault modeling scheme employing horizontal velocity data derived from seven CGPS stations (cooperative University of Utah and the BARGEN network) and Holocene slip rate information from paleoseismic studies. Campaign GPS measurements were made along the central and southern Wasatch fault. Ancillary studies included fault stress interaction to understand the relationships for earthquake triggering of multiple segments on the Wasatch fault, visco-elastic modeling of long term fault behavior, evaluating the effect of GPS derived ground motion on probabilistic fault hazard. And two independent studies of the Wasatch fault included an examination of fault displacement hazard as well as an InSAR analysis of imagery coherency of the Wasatch Front region to assess regional deformation. (See Fig. 1a for continous and campaign GPS station locations and motion vectors from recent measurements).

Results:

Principal Objectives:

The principal objectives of our Wasatch fault geodetic study are essentially to investigate the physics of normal faulting earthquakes and to determine the importance and use of geodetic data on contemporary strain rates as they effect earthquake hazards. The project involves the integration of the extensive geologic information into analytic simulations of fault nucleation including models of co-, post- and perhaps pre-seismic deformation. It includes: 1) GPS monitoring of the Wasatch fault, 2) how state-dependent fault properties and viscoelastic after-slip effect the contemporary loading rate, 3) how these rate-state models apply to nucleation of normal faulting earthquakes, and 4) how this information can be incorporated into earthquake hazard analysis of the populate Wasatch Front.

General Accomplishments:

Under this project the University of Utah focused on continous and campaign GPS measurements and investigating relevant models of normal fault behavior targeted on the Wasatch fault. Because of reduced funding from our proposed project, tasks were reduced to three elements:1) maintenance of four continuous recording GPS sites on the Wasatch Front, Utah, 2) incorporation of data from three Harvard Smithsonian-Cal Tech Basin-Range CGPS stations in the eastern Basin Range, for a total of 7 stations in our processing scheme, 3) implementation of a campaign GPS survey of the southern and central parts of the Wasatch fault, and 4) research on understanding time-varying behavior of the Wasatch normal fault incorporating GPS-derived motions, the paleoseismic record and fault stress interactions. Our main field project includes operation of four University of Utah continuous GPS stations and data processing of nine ancillary CGPS stations (including five from the Harvard/CalTech northern Basin-Range CGPS array) in the surrounding region.

An important aspect of this years research was the implementation of a campaign GPS survey of the Wasatch fault cooperatively with UNAVCO for instruments from their pool and a colleague at BYU, Dr. Ron Harris, who provided 4 GPS receivers at no cost to the project. Also our CGPS data are set up to automatically be sent daily to the UNAVCO archive are web accessible to any user. We also analyzed the paleoearthquake data obtained by trenching on the Wasatch fault and developed a more geologically realizable paleoearthquake time history that is not restricted by the preconceived notion of independent segments that are not affected by rupture on adjacent segments.

Specific efforts included:

- Operating four continuous GPS stations to provide the multiple baseline crossings of the Wasatch fault for monitoring ground deformation.

- Incorporation of data from five ancillary stations of the Northern Basin and Range (BARGEN) array operated by Harvard-Smithsonian and Caltech into our processing scheme.

- Continued upgrade and repair of continuous GPS (CGPS) stations and digital telemetry to withstand rugged, mountainous terrain in cold weather climate.

- Provide daily downloads of CGPS data to the UNAVCO data archive for web access to any interested user at: unavco.ucar.edu/data.

- Completed an error analysis of the paleoearthquake data for the Wasatch Front as input to earthquake hazard models.

- Conducted analytic elastic modeling the GPS data using non-linear inverse methods to determine the geometry and rates of causative faults.

- Began visco-elastic modeling of long term normal fault behavior.

- Began an analysis of how GPS slip rates can be incorporated into probabilistic seismic hazard curves incorporating the corrected late Quaternary slip rates, GPS and historic earthquake data.

- Presented invited and contributed papers on our research at the 2000 Fall Meetings of the American Geophysical Union.

- We conducted an probabilistic fault displacement hazard analysis of the Wasatch fault in an independently funded but closely related project to that our USGS work.

- Began a cooperative InSAR (Interferometric Synthetic Aperture Radar) analysis of Wasatch fault related deformation in an independently funded but closely related project to that our USGS work.

Wasatch Front CGPS Operations

The Wasatch Front CGPS network has been operating for four years (1997-2000). Currently, four stations (RBUT, LMUT, NAIU, and EOUT) are operating and telemetering data to the University of Utah. We also received daily downloads from seven of the Basin-Range (BARGEN) regional GPS network that are incorporated into our daily processing. We currently employ the Y2K compatible Bernese Processing Engine (BPE) to daily process the RINEX data from the four Wasatch Front stations together with data from seven stations from the International Geodetic Service, five from BARGEN, and six from the Yellowstone and Snake River Plain (YSRP) network.

Along with our four CGPS and the five BARGEN stations, these 9 stations form multiple baselines that cross the Wasatch and Oquirrh-Great Salt Lake and subsidiary faults, and are important for estimating the overall crustal deformation of the Wasatch Front (Fig. 1).

Tectonic Setting and Deformation Rates of the Wasatch Fault:

The Wasatch fault has been the focus of extensive geologic and geophysical studies beginning with G.K. Gilbert s pioneering work of the on normal faults at the turn of the 20th century. These studies emphasized the significance and scope of the Wasatch fault within the extensional architecture of the Basin-Range.

Late Quaternary Fault Loading Rates -- Recent studies have elucidated Late Cenozoic slip and exhumation rates of the Wasatch Range and accompanying fault slip of ~1 mm/yr. with up to 11 km of total fault offset (Parry, Bruhn, and Ehlers, Univ. of Utah). New mapping by Harris, BYU, and Friedrich, CalTech, aided by comparisons with Basin-Range seismic reflection profiles of normal faults, has suggested a low-angle geometry of the Wasatch fault, ~ 40 , surprisingly similar to the inverse models of GPS data (below). But they are in contrast to the results from focal mechanism studies of large normal faulting earthquakes across the globe (Jackson, Cambridge; Doser and Smith, Univ. of Utah) that showed an average 55 dip, notably steeper than modeled for the Wasatch fault. These and ancillary seismic and gravity analysis (Smith and Bruhn, Univ. of Utah, Zoback, USGS), as well as seismicity of the Wasatch Front (Arabasz and Smith, Univ. of Utah), provide important background information for our Wasatch fault research.

Further, the Wasatch fault is one of the most, if not the most intensively studied normal faults on the globe. It is the quintessential normal fault because of its 370-km remarkably long length, large offset, and it is active. Twenty seven trenches have been excavated on the fault, most accompanied by geomorphic analyses (Schwartz, Machette, USGS; Christensen, Utah Geol. Survey, McCalpin, Olig and Wong, consultants). These studies revealed Holocene slip-rates of

0.5 to 1.5 mm/yr. Importantly, these studies lead to the definition of characteristic earthquakes where slip occurs repeatedly with constant offsets.

Our research, integrating paleoseismicity and GPS information have suggested 13 (dual-segment) or 17 (single-segment) M7+, scarp-forming earthquakes in the last 5,600 years, with an average return rate of 430 or 350 years, respectively. The last event was more than 600 years ago. However, a mega deep trench excavated in 1999 (McCalpin, 2000, consultant) near Salt Lake City accessed strata as old as Lake Bonneville time, 12,000 years ago, and surprisingly did not reveal any slip on the fault to 5,600 years ago, the age of the oldest event. This implies a ~ 6,000 year hiatus and more importantly, suggests contemporary earthquake clustering. Also Wernicke and others (2000) have suggested that a significant component of Wasatch fault loading rates may be attributed to viscous strain recovery in response to large prehistoric earthquakes.

Contemporary Deformation Rates — On the other hand, EDM (Savage, USGS) and campaign GPS studies, begun in 1972 and now corroborated by continuous GPS measurements by the University of Utah (Smith, Meertens, Martinez, Univ. of Utah; Wernicke, Friedrich, Bennett, CIT; Thatcher, USGS), have revealed horizontal deformation rates that are higher than those implied by the geologic rates. For example, a strain rate of 50 ± 20 nstrain/yr across a 55 km wide network observed, from 1993-1996, by the Univ. of Utah corresponds to deformation rates up to 2.7 ± 1.3 mm/yr spanning the Wasatch fault. These values were corroborated by CGPS measurements that revealed rates increasing south (Provo area) to north of 1.7 (Salt Lake City) to 2.7 mm/yr (Ogden area), averaging ~ 2 mm/yr. These rates are a notable component, 20% of the total Basin-Range opening rate of ~10 mm/yr. (See Fig. 1b. for a comparison of equivalent seismic moment contributions to Wasatch fault deformation from paleoearthquakes, contemporary seismicity and GPS measurements).

InSAR Analysis of the Wasatch fault zone: Studies are supported independently by a preliminary InSAR analysis of Wasatch fault deformation (Sabatier and Feigl, 2000) demonstrated a complex pattern of valley wide, uplift and subsidence from 1992 to 1998. However the data lacked coherency in the footwall block for a complete analysis. None the less, they point out the need to investigate in more detail the relationship between foot- and hanging-wall deformation and how it varies along the entire fault zone. (See Fig. 1b for a summary of various geologic, geodetic and seismic source contributions to earthquake recurrence of the Wasatch fault).

Inverse Modeling of GPS Data -- While the geometry of the Wasatch fault is not known, GPS deformation measurements have been helpful to evaluate this property. We have applied Cerevilli s self-annealing inversion code to the campaign and CGPS data as well as the EDM measurements on the Wasatch fault at Ogden, Salt Lake, Provo and at its southern end (Fig. 2a). The inverse models suggest slip-rates of 5 to 7 mm/yr. on a single, 35° to 50° west dipping normal faults with locking depths of ~15 to 17 km. These rates are notably in excess of the loading rates deduced from the Holocene slip estimated from the trenching measurements. This emphasizes the question of how slip determined on near-vertical fault exposures in alluvium reflects the tectonic loading at seismogenic depths loading inferred by the GPS models. (See Fig. 2 for the results of inverse fault loading model from GPS data on the Wasatch and Qquirrh faults).

1999-2000 Wasatch Front GPS Campaign Survey -- GPS campaign surveys, on the other hand, provide a denser and broader station spacing and will materially add information to the three-dimensional velocity field, especially in areas of multiple fault hangingwall/footwall coverage. During the fall, 1999, and early winter, 2000, the University of Utah, in cooperation with Brigham Young University (at not cost to the project), conducted a GPS field campaign of 43 sites around the Weber, Salt Lake City, Provo, and Nephi segments of the Wasatch fault. These data will be jointly processed with that from previous Wasatch campaigns (1992, 1993, 1994, and 1995) as well as with our CGPS station data. With a time history up to seven years from these surveys, we expect to get much better time and spatial distributed deformation data with lower errors. These results will provide the necessary data for kinematic analyses of the Wasatch fault, including the necessary detail for assessing fault geometry, as well as contemporary information on its aseismic nature. This information is critical input for earthquake hazard assessments.

CGPS Array Operation — Our continuous GPS sites are designed to operate in high mountainous, cold weather conditions planned for unattended operation. The instrumentation includes photo voltaic power (except for Lake Mt.) and digital spread-spectrum radios for telemetry between the sites and the University of Utah GPS recording laboratory. Choke-ring antennas are attached to Invar rods set in four to six foot long boreholes drilled into bedrock. All stations are equipped with Trimble SSi dual-frequency GPS receivers (acquired at no cost to the project by a grant to the University of Utah from the National Science Foundation). Spread spectrum digital radio links to the University of Utah campus provide the GPS data which are then linked to a Sun UltraSparc computer (acquired by the University of Utah at no cost to the project.) Data are sampled at 30-second rates..

Problems Encountered -- This year we have not encountered any major logistical problems.

Non-Technical Summary

Under this research project, the University of Utah conducts research on time-varying behavior of the Wasatch fault by precise measurements of ground motion using continuous-recording GPS (Global Positioning Systems) satellite receivers and investigates the long term fault loading rates on the Wasatch fault from geologic information. The GPS receivers are mounted in bedrock on mountains that surround the populated Wasatch Front. They transmit data to the University of Utah via radio links for recording and processing. The project is a follow-up to confirm measurements from a 1992-1995 temporarily deployment of GPS receivers along the Wasatch fault that revealed unexpectedly high deformation rates of 2 to 3 times faster loading of the fault than deduced from geologic determinations. The new Wasatch Front continuous GPS network also incorporates data from a collaborative regional network of GPS stations across western Utah, northern Nevada and Wyoming. Initial results for the Wasatch fault confirm the high deformation rates determined in our earlier surveys and have important implications for earthquake hazard. We also note that our CGPS data are provided to the local surveying community for high accuracy reference surveying.

Papers, Theses and Presentations Related To Project

Braun, J., 1999, Probabilistic displacement hazard assessment of the Wasatch and surrounding faults, Wasatch Front, Utah, 151 pp (MS thesis University of Utah).

Chang, W. and R. B. Smith, 1999, Stress contagion by large normal-faulting earthquakes and its effects on seismic hazard estimations, Eos, Trans. Amer. Geophys. Un. 80, 46, F1009.

Chang, W. L. and R. B. Smith, 1999, Stress analyses and earthquake history of large historic and paleoearthquakes of the Intermountain region, 1999 Abstracts with Programs, Rocky Mountain Section, Geological Soc. America, v. 31, n. 4, A-7.

Chang, W. L. and R. B. Smith, 1999, Stress analyses of historic and paleoearthquakes in the Intermountain region, 1999 Ann. Meeting and Exposition, Geological Soc. America, A-376-377.

Chang, W. L. and R.B. Smith, 2000, Stress contagion, paleoseismicty and seismic hazard assessment of the Wasatch Front, Utah, Seis. Soc. Am. Bulletin, (in preparation).

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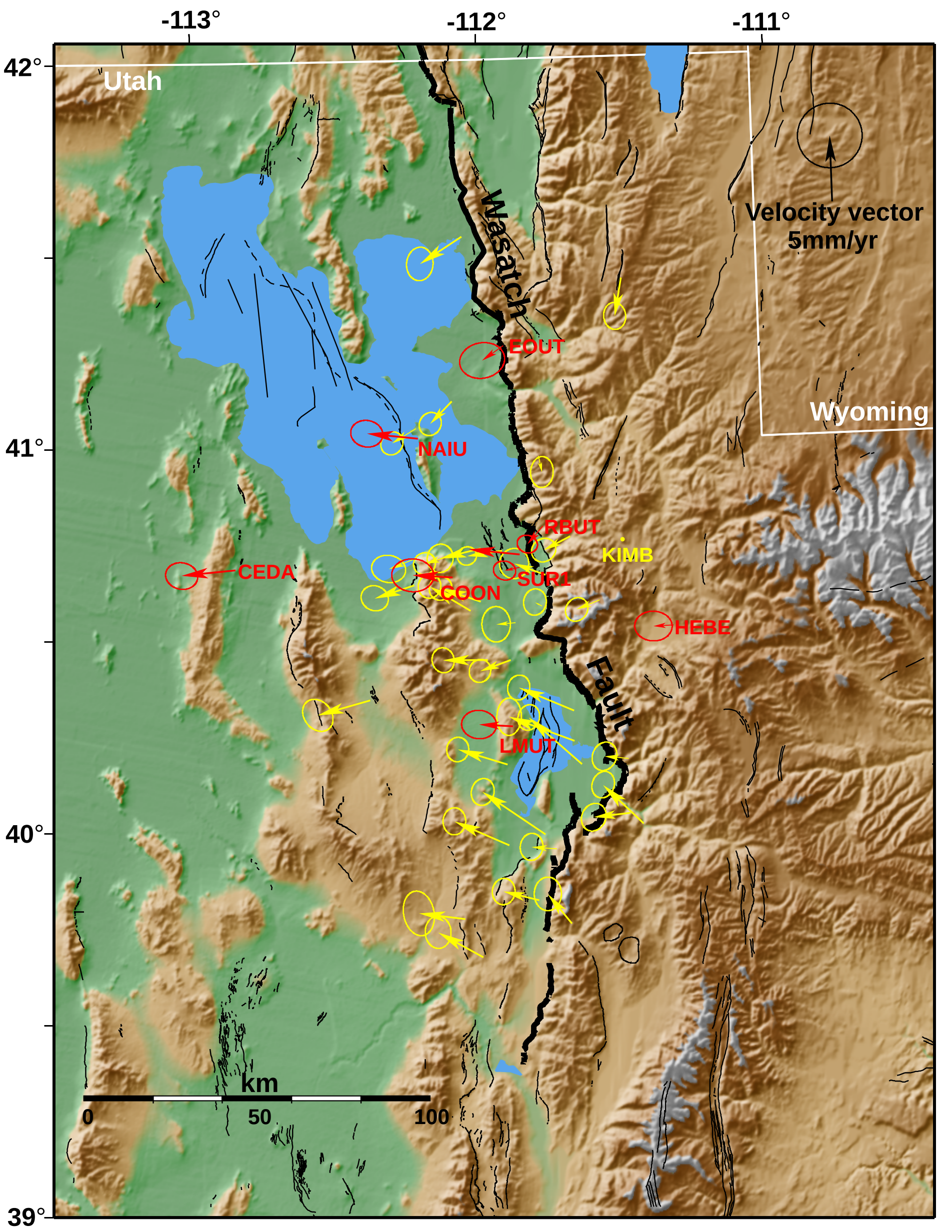
Jouannetaud, D., 2000, Study of the interseismic deformation by InSAR of the Wasatch fault, Utah, USA, Thesis, University Paul Sabatier, Toulouse, 28 pp.

Smith, R. B. and W.L., Chang, C. M. Meertens, and P. Cervelli, 2000, Deformation and fault-modeling on the Wasatch Front, Utah, from continuous and campaign GPS measurements, 1992-1999, Abs. 95th Ann. Meeting, Seismol. Soc. America, Seismol. Res. Letters, v. 71, p. 256.

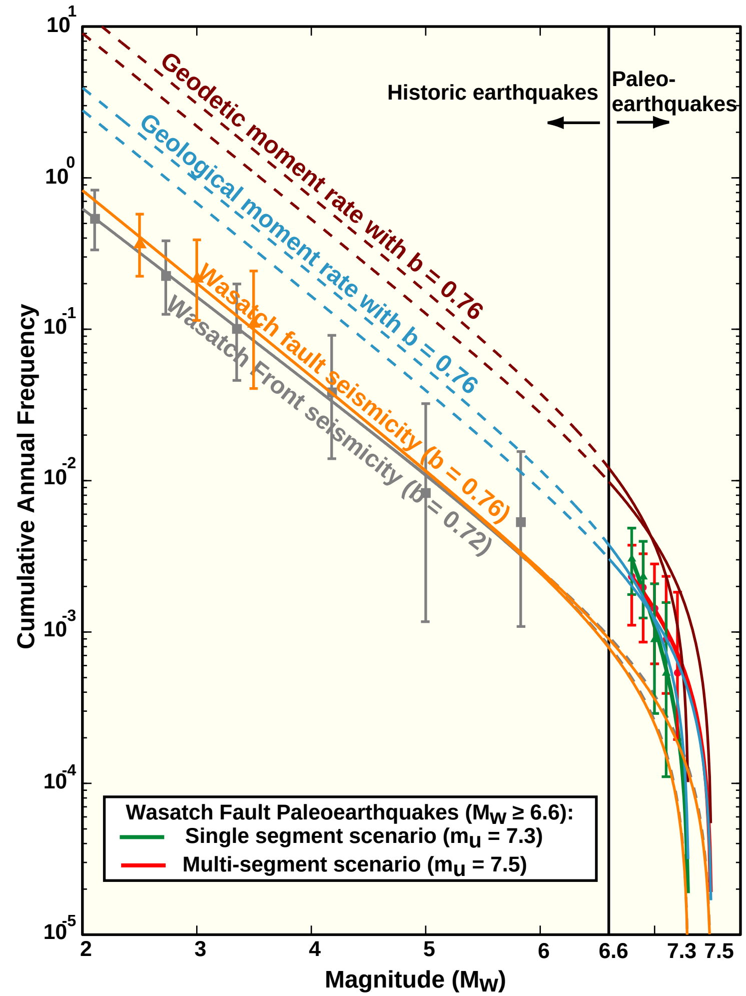
Youngs, R.R. [and multiple authors, including R.B. Smith], 2000. Probabilistic fault displacement hazard analysis (PFDHA): Earthquake Spectra, submitted.

Availability of Data

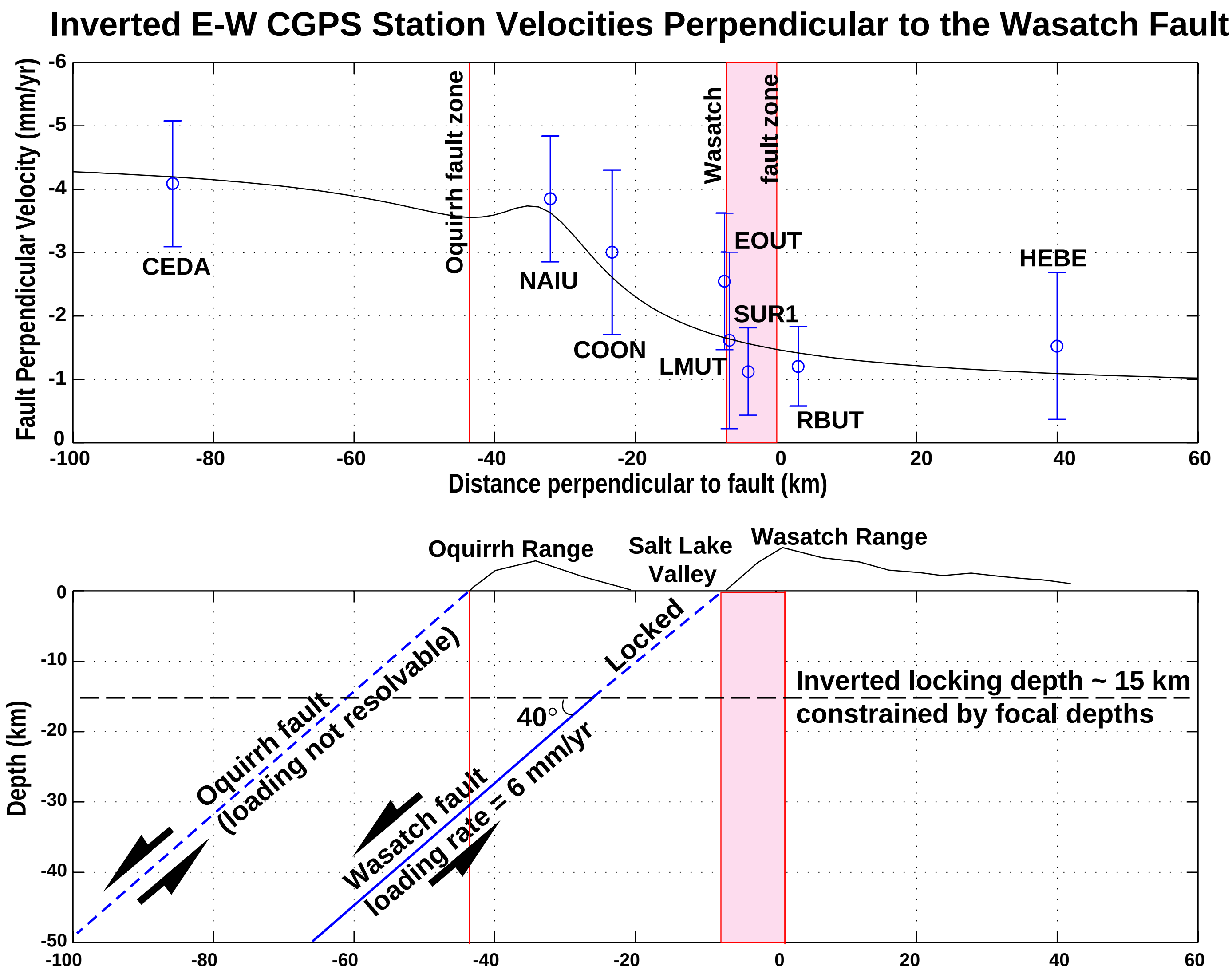
All Wasatch Front campaign and continuous GPS data are archived in Rinex format the UNAVCO (University NAVSTAR consortium) data management center, Boulder, Colorado at unavco.ucar.edu/data. Hourly data from the RBUT station are provided to the National Geodetic Survey and contribute to the NGS CORS on-line network which are accessible by ftp at ftp://cors.ngs.noaa.gov/coord. This component of our research project provides the local surveying community with local base stations. As soon as a reliable automated processing scheme is completed all of our data along with the Northern Basin Range array data will be available on-line.



1a. Velocity vectors (with 2σ errors) determined from continuous (), 1996-2000 and campaign (), 1995-1999, GPS sites in an ITRF framework. CGPS sites operated by the Univ. of Utah and BARGEN (CalTech and Harvard) and processed collaboratively.



1b. Frequency of occurrence curves for the Wasatch fault zone from estimates of historical seismicity, paleoseismicity and campaign GPS results.



2. Preliminary inversion results showing that the data are best fit by a single north-south striking infinite-edge dislocation. It corresponds to a west dipping ~ 40° normal fault extending eastward toward the surface expression of the Wasatch fault, with a locking depth of 15 km and a creeping segment slip rate of ~ 6 mm per year.